# 14.452 Economic Growth: Lecture 12, Beyond Factor-Augmenting Technological Change

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# Introduction

- Thus far we have followed almost the entire macroeconomic and economic growth literatures, and focused on factor-augmenting technologies (Harrod neutral or skilled labor and unskilled labor augmenting).

- Does this matter?

- It is certainly convenient. But it is also very restrictive, and we will see that it has a range of (often unrecognized) implications.

- This lecture will develop one alternative building on "*task-based*" production.

# Motivation I

- Huge slowdown in wage and employment growth in the US over the last several decades.
- Behavior of wage bill normalized by population:
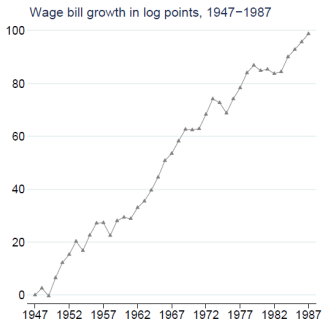
## Motivation II

- A corresponding change in the distribution of national income between capital and labor (both in the US and elsewhere)
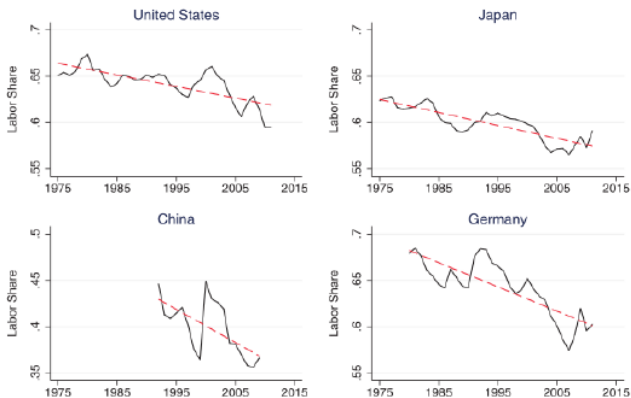


FIGURE II

Declining Labor Share for the Largest Countries

figure shows the labor share and its linear trend for the four largest economies in the world from 1975.

# Motivation III

- Can we understand these using a framework with just factor-augmenting technologies?

- We will see that the answer is most likely no (because given reasonable elasticities of substitution between capital and labor, you cannot generate such huge changes in the factor distribution of national income).

- But there are also other aspects of the factor-augmenting technology that is problematic which I will now develop in the context of the skill bias of technology and the skill premium.

# SBTC: Canonical Approach

- Constant elasticity of substitution (CES) production function with two inputs (skilled and unskilled labor):

$$Y(t) = \left[ \gamma_L \left( A_L(t) L(t) \right)^{\frac{\sigma-1}{\sigma}} + \gamma_H \left( A_H(t) H(t) \right)^{\frac{\sigma-1}{\sigma}} \right]^{\frac{\sigma}{\sigma-1}},$$

where

  - $A_L(t)$ and $A_H(t)$ are two separate technology terms.
  - $\gamma_i$s determine the importance of the two factors, $\gamma_L + \gamma_H = 1$.
  - $\sigma \in (0, \infty)$=elasticity of substitution between the two factors.

- A formalization of Tinbergen's "race between education and technology".
- For example, Katz and Murphy (1992).

# Empirical Implementation (Katz and Murphy)

- Combining these equations:

$$\ln \omega = \frac{\sigma - 1}{\sigma} \ln \left( \frac{A_H}{A_L} \right) - \frac{1}{\sigma} \ln \left( \frac{H}{L} \right).$$

- Now following Tinbergen, posit

$$\ln \left( \frac{A_{H,t}}{A_{L,t}} \right) = \gamma_0 + \gamma_1 t,$$

- Then:

$$\ln \omega_t = \frac{\sigma - 1}{\sigma} \gamma_0 + \frac{\sigma - 1}{\sigma} \gamma_1 t - \frac{1}{\sigma} \ln \left( \frac{H_t}{L_t} \right).$$

- Estimating this for 1963–1987, following Katz and Murphy (1992), we obtain

$$\ln \omega_t = \quad \text{constant} \quad + \underset{(0.005)}{0.027 \times t} \quad - \underset{(0.128)}{0.612 \cdot \ln \left( \frac{H_t}{L_t} \right)}$$

- Success? Not really. There are four related but distinct problems.

# Problem 1

- Factor-augmenting technologies lack descriptive realism.
- Are computers skill biased?
- This would literally mean that they increase the productivity of labor uniformly in everything. But they clearly do not do that. Skilled laborers performing manual tasks will not experience such an increase, nor will workers providing entertainment.
- What about robots? It is difficult to imagine robots as directly increasing the productivity of any type of worker — they are meant to perform tasks that were previously performed by labor.

# Problem 2

- Bad out of sample prediction of Katz-Murphy type regressions.
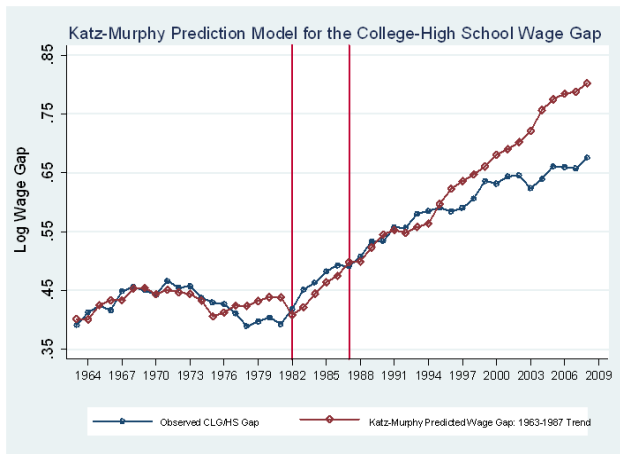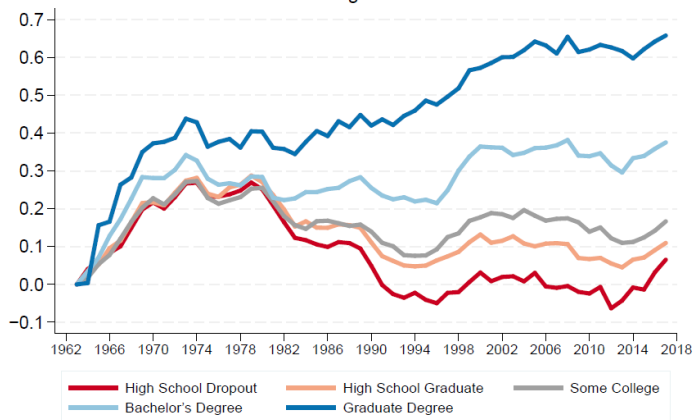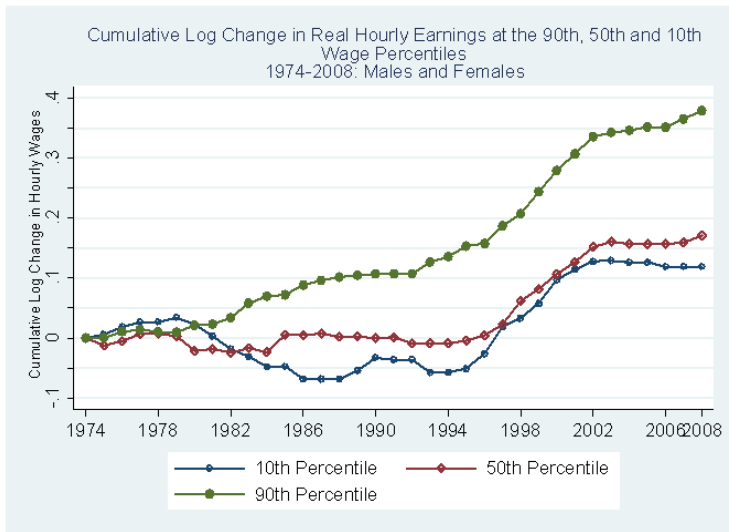
# Problem 3

- Declining real wages (without technological **regress**, there should be no wage declines for any group).



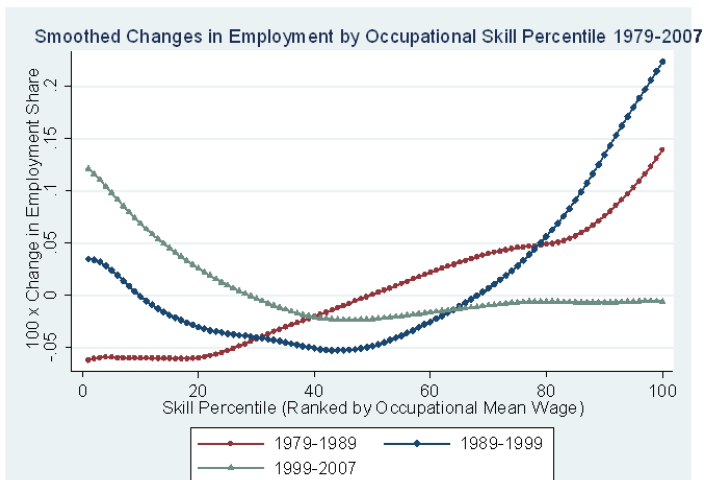Cumulative Change in Log Weekly Earnings 1963 − 2017
Men Ages 16−64

# Problem 3 (continued)
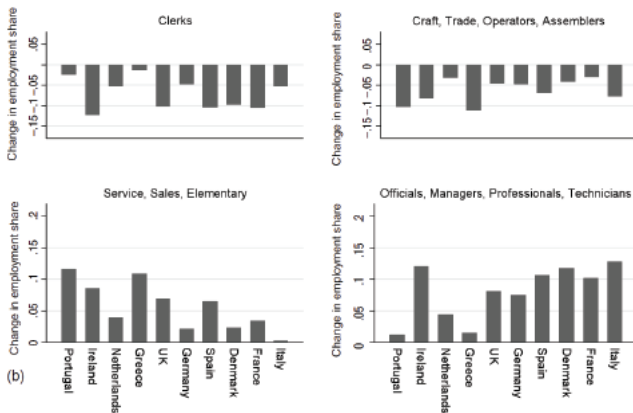
# Problem 4

- No occupational evidence for skill-biased change since the 1990s (Acemoglu and Autor, 2011).



Smoothed Changes in Employment by Occupational Skill Percentile 1979-2007

# Problem 4 (continued)

- Not just confined to the US.

# Alternative: Task-Based Production

- An alternative that avoids these problems and makes progress in clarifying what might be going on is a task-based framework based on Zeira (1998), Acemoglu and Zilibotti (2000), Autor, Levy and Murnane (2003), Acemoglu and Autor (2011) and Acemoglu and Restrepo (2018, 2019, etc.).
- Main idea:
  - Give up the aggregate production function with factor-augmenting technological changes (what are they anyway?)
  - Consider the **allocation of tasks to factors** as the major economic choices affecting the demand for different types of factors.
- A more micro approach.
- But more importantly, very different comparative statics and implications.

# Formal Model

- There is a unique final good (or alternatively a particular type of good in a specific sector) $Y$ produced by combining a continuum of tasks $y(i)$, with $i \in [N-1, N]$.

$$Y = \left( \int_{N-1}^{N} y(i)^{\frac{\sigma-1}{\sigma}} \, di \right)^{\frac{\sigma}{\sigma-1}}, \sigma \in (0, \infty) : \text{ elasticity of substitution.}$$

- Set the resulting ideal price index as numeraire.
- The range $N-1$ to $N$ implies that the set of tasks is constant, but older tasks might be replaced by new (more complex and more productive) versions thereof.
- Namely, an increase in $N$ adds a new task at the top while simultaneously replacing one at the bottom.
  - This structure is adopted for simplicity. Similar results with less clean algebra if integration is between $[0, N]$.
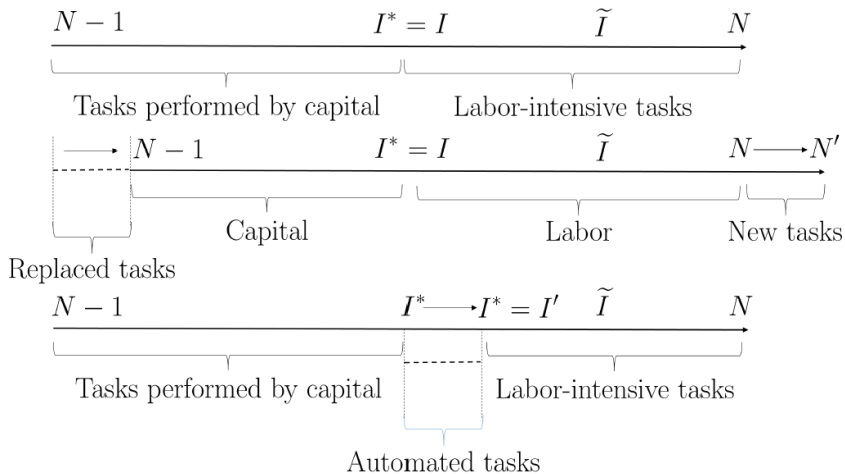
# Task Production Function

- Tasks with $i \leq I$ are technologically **automated**, and can be produced with labor or capital.
- Tasks with $i > I$ are not technologically automated yet, and can only be produced with labor.
- This means:
$$Y(z) = \begin{cases} A^L \gamma^L(z) l(z) + A^K \gamma^K(z) k(z) & \text{if } z \in [N-1, I] \\ A^L \gamma^L(z) l(z) & \text{if } z \in (I, N]. \end{cases}$$
- *Comparative advantage:* $\gamma^L(z)/\gamma^K(z)$ increasing in $z$ — higher index tasks should be allocated to labor.
- Factor-augmenting technologies still present (for comparison and empirical analysis), and changes in $\gamma^L(z)$ and $\gamma^K(z)$ generate task-specific productivity changes.
- *More importantly:* increases in $I$ correspond to automation (at the extensive margin) and increases in $N$ capture creation of new tasks
- The assumption that labor-intensive tasks use no capital can be relaxed

# Allocation of Tasks to Factors: Summary



$$N-1 \qquad\qquad I^* = I \qquad\qquad \widetilde{I} \qquad\qquad N$$

Tasks performed by capital      Labor-intensive tasks

$$N-1 \qquad\qquad I^* = I \qquad\qquad \widetilde{I} \qquad\qquad N \longrightarrow N'$$

Capital                    Labor              New tasks

Replaced tasks

$$N-1 \qquad\qquad I^* \longrightarrow I^* = I' \quad \widetilde{I} \qquad\qquad N$$

Tasks performed by capital      Labor-intensive tasks

Automated tasks

# Factor Supplies

- At any point in time the stock of capital is fixed at $K$ and capital is rented at a price $r$ (determined endogenously).
- Suppose labor is inelastically supplied (easy to relax) and commands a wage $W$.
- Market clearing:

$$
\begin{aligned}
L &= \int_{N-1}^{N} l(z)dz \\
K &= \int_{N-1}^{N} k(z)dz.
\end{aligned}
$$

# Equilibrium

- In equilibrium, all tasks below some threshold $I^* \leq I$ are automated (allocated to capital) and the rest are allocated to labor.

- Suppose
$$I^* = I.$$

- This will be the case when the capital to labor ratio or the wage to rental rate ratio are intermediate — in particular, when

$$\frac{1 - \Gamma(I, N)}{\Gamma(I, N)} \left( \frac{A^L}{A^K} \frac{\gamma^L(I)}{\gamma^K(I)} \right)^{\sigma} < \frac{K}{L} < \frac{1 - \Gamma(I, N)}{\Gamma(I, N)} \left( \frac{A^L}{A^K} \frac{\gamma^L(N)}{\gamma^K(N-1)} \right)^{\sigma}.$$

Or when

$$\frac{A^L}{A^K} \frac{\gamma^L(I)}{\gamma^K(I)} < \frac{W}{R} < \frac{A^L}{A^K} \frac{\gamma^L(N)}{\gamma^K(N-1)}.$$

# Equilibrium Production Function

- Under these assumptions, we have a "derived" constant elasticity of substitution expression for output:

$$Y = \Pi(I, N) \left( \Gamma(I, N)^{\frac{1}{\sigma}} \left( A^L L \right)^{\frac{\sigma-1}{\sigma}} + (1 - \Gamma(I, N))^{\frac{1}{\sigma}} \left( A^K K \right)^{\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}.$$

- In particular, let us define the *task content of production* as

$$\Gamma(I, N) = \frac{\int_I^N \gamma^L(z)^{\sigma-1}}{\int_{N-1}^I \gamma^K(z)^{\sigma-1} dz + \int_I^N \gamma^L(z)^{\sigma-1}}.$$

The TFP term is then

$$\Pi(I, N) = \left( \int_{N-1}^I \gamma^K(z)^{\sigma-1} dz + \int_I^N \gamma^L(z)^{\sigma-1} \right)^{\frac{1}{\sigma-1}}.$$

- Major difference from factor-augmenting models: the distribution parameters of the CES are endogenous because of the *changes in the task content of production* as a result of technological change.

# Equilibrium: The Labor Share

- The labor share, $WL/Y$, is given as

$$s^L = \frac{1}{1 + \frac{1-\Gamma(I,N)}{\Gamma(I,N)} \left( \frac{A^L}{W} \frac{R}{A^K} \right)^{1-\sigma}}.$$

- **Key result**: separation of the effects of factor-augmenting technological changes and the task content of reduction.
- The elasticity of substitution intermediates only the former.

# Equilibrium: Technology and Labor Demand

- For a given level of factor utilization, $L$ and $K$, labor demand from the sector can be written as

$$W^d(L, K; \theta) = \frac{Y(L, K; \theta)}{L} \times s^L(L, K; \theta).$$

- Labor demand $W^d(L, K; \theta)$ is decreasing in $L$ and increasing in $K$ as should be expected.

# Comparative Statics with Factor-Augmenting Technologies

- The comparative statics of labor demand with respect to factor-augmenting technologies are identical to those in the standard model.

$$
\frac{\partial W^d(L, K; \theta)}{\partial \ln A^L} = s^L(L, K; \theta) \qquad \text{(Productivity effect)}
$$
$$
+ \frac{\sigma - 1}{\sigma}(1 - s^L(L, K; \theta)) \quad \text{(Substitution effect)},
$$
$$
\frac{\partial W^d(L, K; \theta)}{\partial \ln A^K} = (1 - s^L(L, K; \theta)) \qquad \text{(Productivity effect)}
$$
$$
+ \frac{1 - \sigma}{\sigma}(1 - s^L(L, K; \theta)) \quad \text{(Substitution effect)}.
$$

- *Productivity effect* always positive: lower cost/higher productivity mean more labor demand (higher wages and/or employment).
- *Substitution effect* positive or negative depending on whether $\sigma > 1$ or not (and whether labor or capital is becoming more productive).

# Factor-Augmenting Technologies (continued)

- Overall impact on labor demand always positive from $A^K$ and also positive from $A^L$ so long as $\sigma$ is not too low (greater than $1 - s^L$ suffices).
- Impact on the labor share depends on whether $\sigma > 1$.
- In particular, when $\sigma = 1$, the substitution effect is zero, and labor demand changes proportionately with factor-augmenting technologies.
- This implies the labor share is constant.
  - The labor share falls with $A^K$ when $\sigma > 1$ and falls with $A^L$ when $\sigma < 1$.
  - But when $\sigma$ is close to 1, not much change in the labor share in response to factor-augmenting technologies.

# Comparative Statics with Automation

- Very different results from automation:

$$\frac{\partial \ln W^d(L, K; \theta)}{\partial I} = \frac{\partial \ln Y(L, K; \theta)}{\partial I} + \qquad \text{(Productivity effect)}$$

$$\frac{1}{\sigma} \frac{1 - s^L(L, K; \theta)}{1 - \Gamma(I, N)} \frac{\partial \ln \Gamma(I, N)}{\partial I} \quad \text{(Displacement effect)}.$$

- *The displacement effect* results from the direct displacement of labor as some tasks are automated, and is negative.
- **Immediate implication:** automation *always reduces* the labor share (regardless of the value of $\sigma$).
- The productivity effect is

$$\frac{\partial \ln Y(L, K; \theta)}{\partial I} = \frac{1}{\sigma - 1} \left[ \left( \frac{R}{A^K \gamma^K(I)} \right)^{1-\sigma} - \left( \frac{W}{A^L \gamma^L(I)} \right)^{1-\sigma} \right] > 0.$$

# Comparative Statics with Automation (continued)

- When new automation technologies are **"so-so"** (meaning that the effective cost of producing with automation is approximately the same as the effective cost of producing with labor), then $\partial \ln Y(L, K; \theta)/\partial I \approx 0$ and the productivity effect is essentially zero.

- Then automation **reduces** labor demand — it reduces wages and/or employment.

- The same is possible even when automation increases productivity, but creates an even bigger displacement effect.

# Comparative Statics with New Tasks

- Opposite results with the introduction of new tasks:

$$\frac{\partial \ln W^d(L, K; \theta)}{\partial N} = \frac{\partial \ln Y(L, K; \theta)}{\partial N} + \qquad \text{(Productivity effect)}$$

$$\frac{1}{\sigma} \frac{1 - s^L}{1 - \Gamma(I, N)} \frac{\partial \ln \Gamma(I, N)}{\partial N} \quad \text{(Reinstatement effect)}$$

- *The reinstatement effect* is always positive, so labor demand always expands and does so more than proportionately with the productivity effect.

- Hence, new tasks always increase the labor share.

# Aggregating Across Sectors

- The above framework ignores "*composition effects*" — reallocation of labor and capital across sectors with different factor shares and demands.
- To do this, suppose now that there are $N$ sectors, each with the technology vector $\theta_i = \{I_i, N_i, A_i^L, A_i^K\}$. ($\gamma_i^L$ and $\gamma_i^K$ also differ across sectors but we hold them fixed for simplicity).
- Let $L_i$ and $K_i$ be the (equilibrium) quantities of labor and capital used in each sector, and suppose that factor prices can also differ across sectors.
- Value added of sector $i$ is $Y_i = Y(L_i, K_i; \theta_i)$.
- *Task content of production* in sector $i$ is $\Gamma_i = \Gamma(N_i, I_i)$ and labor share is $s_i^L$.
- GDP is $Y = \sum_{i \in \mathcal{I}} P_i Y_i$ and the economy-wide labor share is $s^L$.
- Also let $\ell_i = \frac{W_i L_i}{WL}$ and $\chi_i = \frac{P_i Y_i}{Y}$ as the share of sector $i$'s in total value added.

# Decomposing Labor Demand

- Changes in economy-wide wage bill, $WL$, can then be exactly decomposed as

$$
\begin{aligned}
d\ln(WL) = \, & d\ln Y && \text{(Productivity effect)} \\
& + \sum_{i\in\mathcal{I}} \frac{s_i^L}{s^L} d\chi_i && \text{(Composition effect)} \\
& + \sum_{i\in\mathcal{I}} \ell_i \frac{1-s_i^L}{1-\Gamma_i} d\ln\Gamma_i && \text{(Change task content)} \\
& + \frac{\sum_{i\in\mathcal{I}} \ell_i (1-\sigma)(1-s_i^L)\cdot}{\left( d\ln\left(\frac{W_i}{A_i^L}\right) - d\ln\left(\frac{R_i}{A_i^L}\right) \right)} && \text{(Substitution effect)}
\end{aligned}
$$

- Changes in wage bill can be viewed as a summary measure of changes in labor demand.

# Comments

- This derivation does not require factor prices to be equal across sectors, and so it can accommodate several different assumptions on factor mobility, heterogeneous types of labor and how factor payments are determined.

- It is exact in continuous time, and in discrete time it would be based on the usual approximations (then the order in which different terms are put may matter, but does not in practice).

- It can be expanded to include different types of labor, but this is not important for our focus here.

- It applies to any changes in the environment.

- Let us focus on changes in technologies summarized by the vector $\theta = \{\theta_i\}_{i \in \mathcal{I}}$.

# Interpretation

- *The productivity effect* is the sum of the contributions from various sources of technology to value added and thus GDP. It can be approximated by changes in (log) GDP per capita.
- *The composition effect* captures changes in labor demand resulting from reallocation of value added across sectors — related to the gap between the labor share of contracting and expanding sectors. The exact expression for the composition effect can be computed from data on industry value added and labor shares.
- *The substitution effect* is an employment-weighted sum of the substitution effects of industries, and thus depends on industry-level changes in effective factor prices and the elasticity of substitution $\sigma$
  - We compute this term using the estimate of the elasticity of substitution from Oberfield and Raval (2014), $\sigma = 0.8$.
  - In practice, fairly insensitive to the exact value of $\sigma$.
  - Also benchmark: $A_i^L / A_i^K$ grows at a common rate across sectors equal to aggregate labor productivity (the exact rate is not important).

# Mapping the Decomposition to Data

- *The change in task content* is given by an employment-weighted sum of the changes in task content of production of industries.
- At each industry this can be computed as a residual.

Change in task content in $i$ =Percent change in labor share in $i$
$$- \text{Substitution effect in } i.$$

- Intuitively, with competitive factor and product markets, the change in task content of production and the substitution effect are the only forces impacting the labor share of an industry. Hence, changes in task content can be inferred once we have estimates of the substitution effect.
- Then compare estimated changes in task contents to other measures of automation and new tasks.

# Mapping the Decomposition to Data   (continued)

- Under the additional assumption that there is no automation and new tasks taking place simultaneously in an industry in a given year, industry changes in task content can be decomposed into *displacement effects* and *reinstatement effects*.

- If there are simultaneous automation and new tasks, then these estimates are under-stated.

# Labor Share and Value Added Across Broad Sectors, 1947-1987
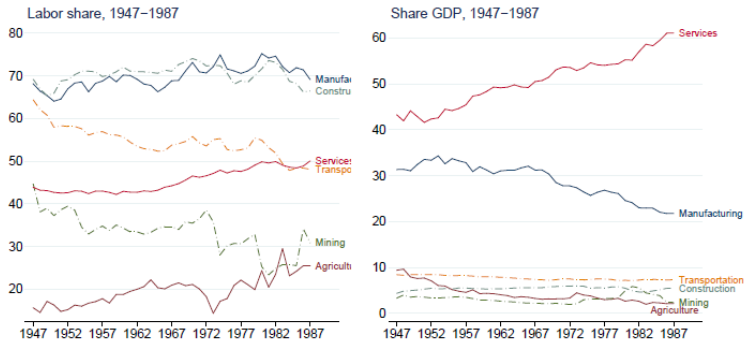


Figure: The labor share and sectoral evolutions, 1947-1987.

- Relatively stable labor shares (important to do labor share in value added, not shipments).

# Labor Demand Decomposition, 1947-1987
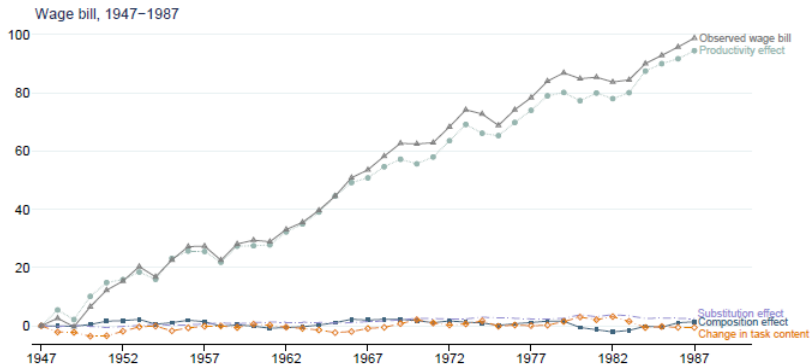


Figure: Sources of changes in labor demand, 1947-1987.

# Why No Change in Task Content?

- *Answer:* Counterbalancing displacement and reinstatement effects.
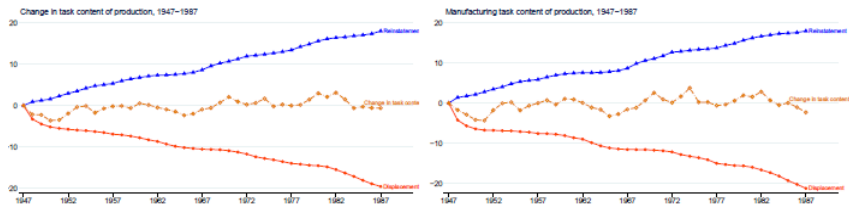


Figure: Estimates of the displacement and reinstatement effects, 1947-1987.

# Labor Share and Value Added Across Broad Sectors, 1987-2017
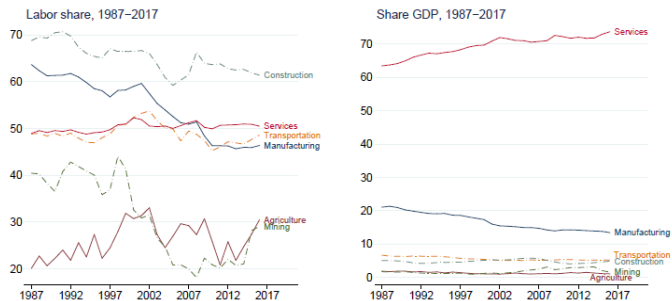


Figure: The labor share and sectoral evolutions, 1987-2017.

- Very different pattern in manufacturing and mining than in 1947-1987. But labor share fairly stable in other industries.

# Labor Demand Decomposition, 1987-2017
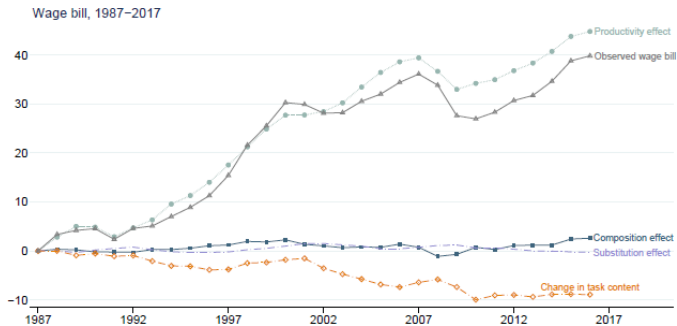


Figure: Sources of changes in labor demand, 1987-2017.

- Decline in the wage bill due to slow down and the productivity effect and large negative changes in task content.
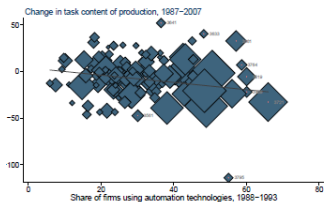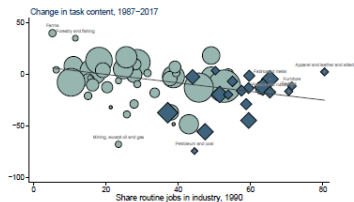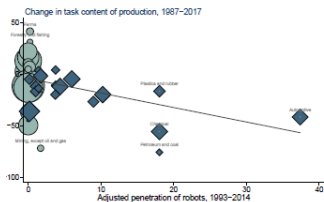
# Why Negative Changes in Task Content?

- *Answer:* Acceleration in displacement and slowdown in reinstatement.
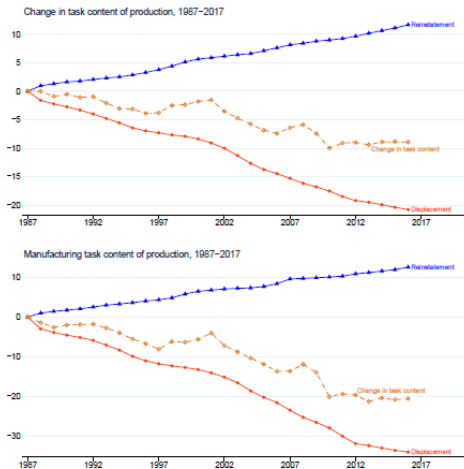
# Changes in Task Content and Automation

- Strong correlation between measures of automation (robots, automation technologies, routine tasks in production) and negative changes in task content at the industry level.
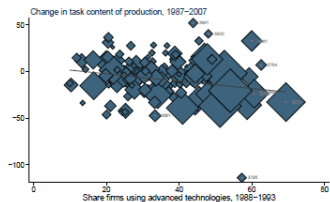
# Changes in Task Content and New Tasks

- Strong correlation between measures of new tasks (new occupations, activities or greater occupational diversity) and positive changes in tasks content.
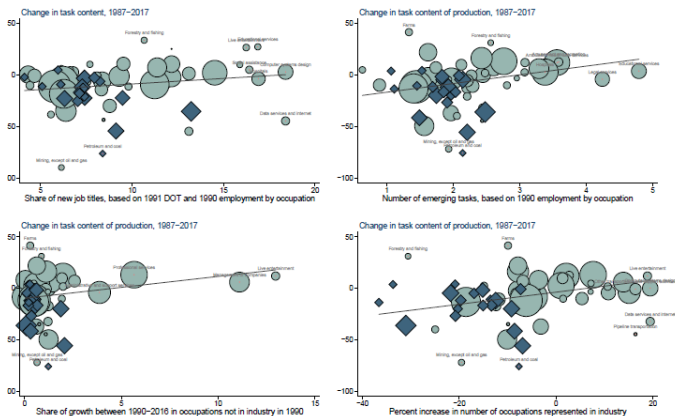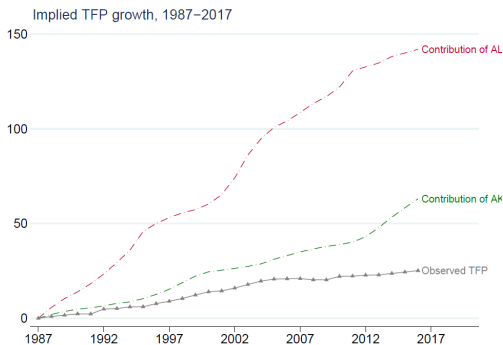


Figure: New tasks and change in task content of production.

# Why We Need Changes in Task Content

- If there are no changes in task content and no negative changes in $A^L$ and $A^K$, then to rationalize industry-level changes in factor shares you need huge technological advances.



- This is because factor-augmenting technological changes have relatively small effects on factor shares.

# Incorporating Growth

- This setup can be embedded into a growth model and is in fact consistent with balanced growth if automation and new tasks take place at commensurate rates.

- Following Acemoglu and Restrepo (2018) suppose:

$$\gamma^K(i) = \gamma^K \text{ and } \gamma^L(i) = e^{Bi} \text{ with } B > 0.$$

- Represent the path of technology as

$$n(t) = N(t) - I(t).$$

- Then if $n(t)$ asymptotically converges to a constant, there is balanced growth.

- *Intuition:* automation is balanced by the creation of new tasks (as we observe in the US data between 1947 and 1987).

# Why Balance?

- Why should we expect balance between automation and new tasks?
- Acemoglu and Restrepo (2018): *directed technological change*.
- Faster automation reduces the labor share significantly, and makes the creation of new tasks more profitable.
- Does this imply that the current decline in the labor share will be reversed?
- Not necessarily:
  - Large changes in technology can push the economy out of the basin of attraction of BGP (towards Leontief's "horse equilibrium").
  - Changes in the innovation possibilities frontier may lead to a different stable equilibrium, with the lower labor share.
  - Inefficiencies.

# Inefficiencies in the Task-Based Framework

- New sources of inefficiencies—typically in the direction of **excessive automation:**
  - Labor market imperfections (increasing the wage above the social opportunity cost) can lead to inefficient automation
  - Automation may affect bargaining.
  - Other social effects from lower labor share, job loss etc.
  - Tax policy excessively favorable to capital and indirectly to automation—Acemoglu, Manera and Restrepo (2020), effectiv taxes on labor around 25%, while on capital they have fallen to around 5%, triggering excessive automation.

# Conclusion

- In many problems in macro, labor and other areas, it may be fruitful to go beyond purely factor-augmenting technologies.
- Different comparative statics, different interpretations and different welfare consequences.
- The empirical evidence appears to be consistent with task-based approaches and not so much with models with purely labor-augmenting or capital-augmenting technologies.
- Still much theoretical and empirical work to be done here.